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TIME DOMAIN ELECTROMAGNETIC SURVEYS FOR ASSISTING IN DETERMINING THE GROUNDWATER RESOURCES ON QUEEN LILIUOKALANI TRUST PROPERTY ISLAND OF HAWAII

Project Number 5067

March 2007

Prepared For:

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1.0 INTRODUCTION

This report contains the procedures and results of surface Time Domain Electromagnetic (TDEM) geophysical surveys performed for groundwater resource evaluation on Queen Liliuokalani Trust property located at the Keahuolu Tract on the Island of Hawaii. ZAPATA ENGINEERING Blackhawk Division (Blackhawk) conducted the surveys from January 27 to January 30, 2007 for Tom Nance Water Resource Engineering (TNWRE) of Honolulu, Hawaii and Queen Liliuokalani Trust (QLT) of Honolulu, Hawaii.

The main objective of the TDEM surveys was to explore for additional high-level groundwater occurrences in the immediate vicinity of the existing 1.0 MG Water Tank located on QLT property above the Mamalahoa Highway. The surveys were conducted at three additional sites to help determine the optimum location for a future groundwater well located near the QLT Water Tank. Figure 1-1 shows the locations of TDEM soundings taken during the 2007 and 1991 surveys on QLT property.

TDEM is a geophysical method that determines from the surface the geoelectric section (resistivity layering) of the subsurface. From the geoelectric section, information about geology and water quality can be inferred. This is possible because the electrical resistivity of the earth depends on lithology, porosity, the degree of saturation, and concentration of dissolved solids in the groundwater. Geophysical surveys, combined with other hydrogeologic information, are used to provide optimum locations for well placement and well completion depths.

2.0 GEOLOGY/HYDROGEOLOGY

Groundwater resources occur on the Hawaiian Islands basically in two modes:

- In a basal mode where a lens of fresh water floats on seawater, and
- In a high-level mode where the fresh groundwater occurrence is controlled by damming structures (i.e. intrusives, dikes, etc).

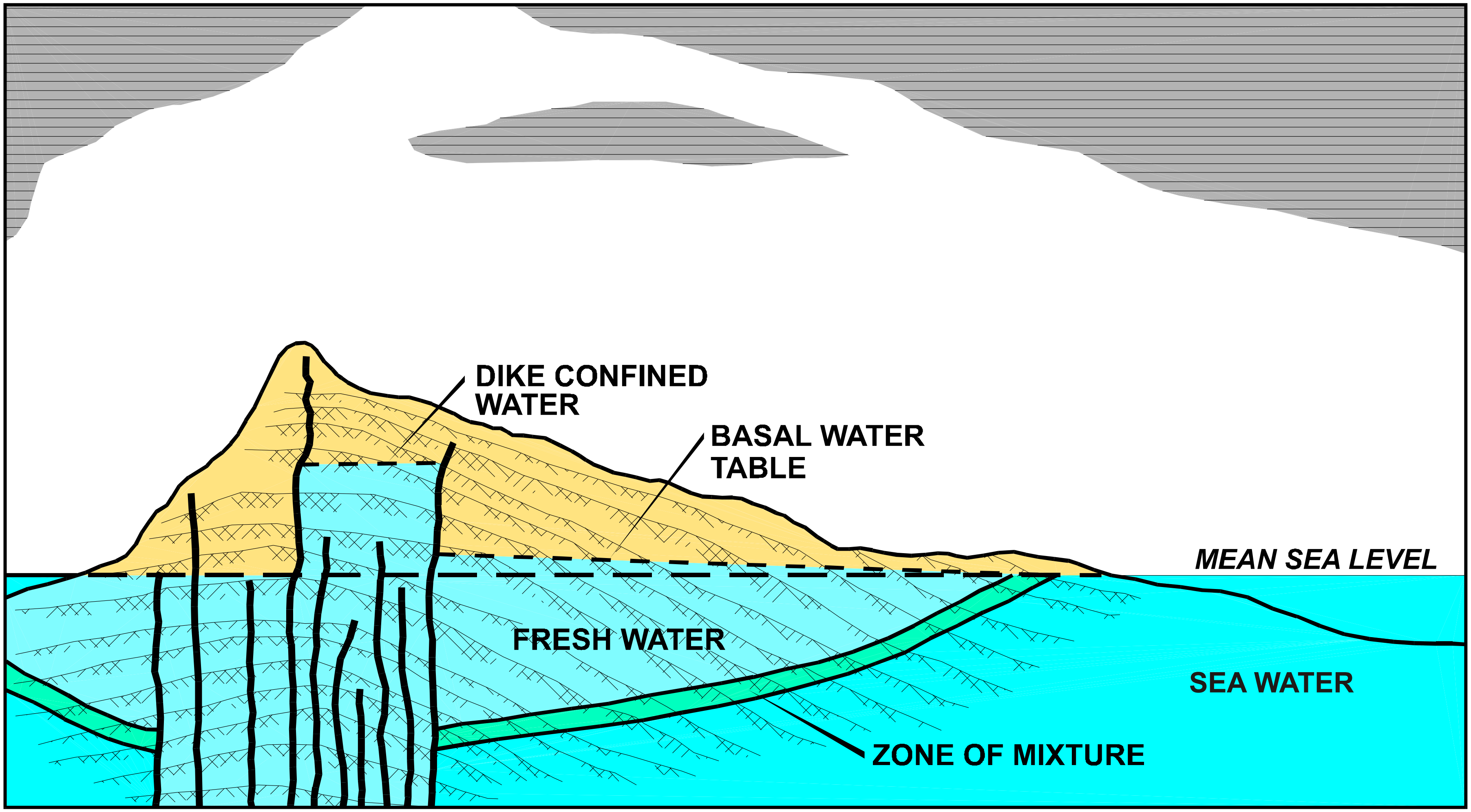
The basic geologic and hydrologic framework of the Island of Hawaii and the two modes of groundwater occurrences are illustrated in Figure 2-1. Fresh groundwater may also occur in areas between these two modes, but production is expected to be highly variable. TDEM surveys previously run on Hawaii have reliably mapped the basal mode groundwater occurrence and the boundary between fresh water in the basal mode and high-level water occurrences.

Basal mode groundwater is resting approximately at sea level near the ocean surrounding the Island of Hawaii. This is generally due to the fact that the volcanic rocks, which comprise the island, allow rainfall to percolate with little impedance directly downward through the rock mass (reference Figure 2-1). The fresh water floats directly on seawater encroaching from the ocean. Fresh water flows laterally toward the ocean causing the fresh water lens to be thinner near the ocean. When groundwater is under conditions of static equilibrium, the Ghyben-Herzberg Principle states that for every one foot of fresh water above sea level, approximately 40 feet of fresh water will exist below sea level as shown in Figure 2-2. The transition from fresh water to seawater at depth may be relatively sharp (i.e. occurring over several tens of feet) or more gradual, depending upon hydrologic flux, horizontal and vertical permeability contrast, and other geologic factors. It is assumed, when resolving TDEM sounding data, that seawater saturated volcanics begin at the midpoint of the transition zone.

TDEM surveys are utilized to map the resistivity stratification of the subsurface. From numerous previous TDEM surveys and calibration at well sites, characteristic ranges of subsurface resistivities have been derived for the geologic/hydrologic units shown in Figure 2-3. Some overlap in resistivity occurs between the units; however, other factors (such as elevation) can be used to help separate the units. Therefore the main geologic/hydrologic units that can be derived from TDEM surveys are:

- Depth to seawater saturated volcanic rocks. This occurs in basal mode situations, and by using the Ghyben-Herzberg Principle, the thickness of the basal fresh water lens can be calculated.
- Weathered volcanic layers (laterite). These lower resistivity units are generally relatively thin (100 ft to 200 ft thick) layers that occur mainly at or near the ground surface.
- Clay poor and fresh water saturated volcanic rocks. These formations generally exhibit high resistivity values. Note that the extent of fresh water saturation is normally based on geographic and elevation information, and that fresh water cannot be directly detected in the TDEM data.

Groundwater damming structures (i.e. intrusives, dikes) are inferred with TDEM data by uncharacteristic sounding curves (distorted by 2-D structures), and by soundings that transition between detection of seawater at depth (indicating basal mode groundwater) and soundings that map high resistivities to depths below sea level (indicating high-level groundwater).



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Schematic Hydrogeologic Cross Section
Island of Hawaii

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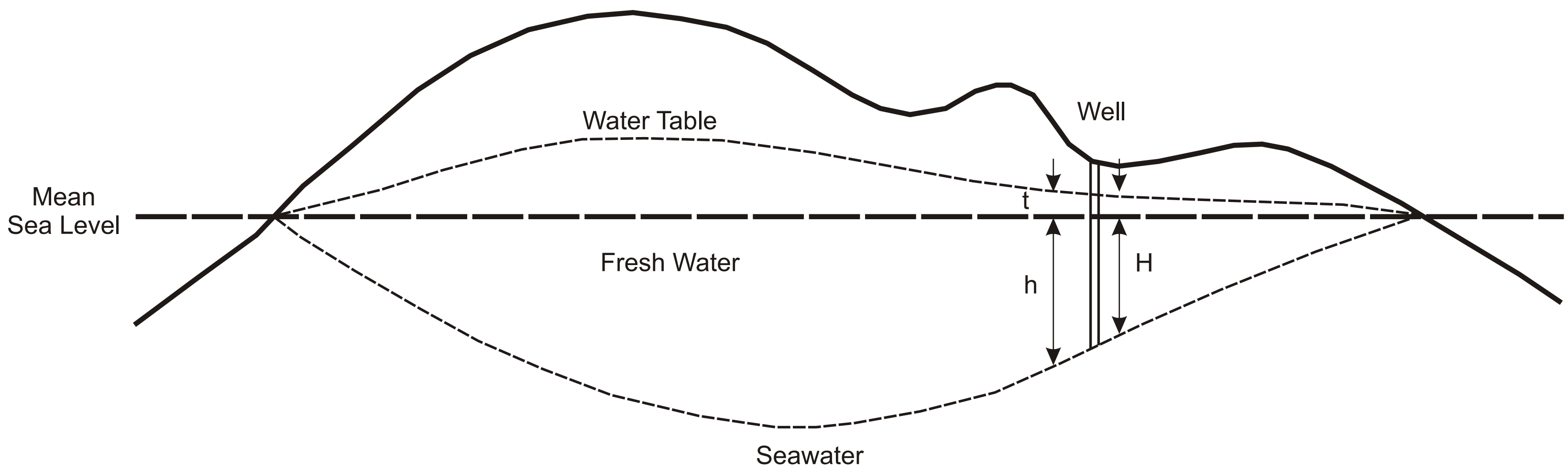
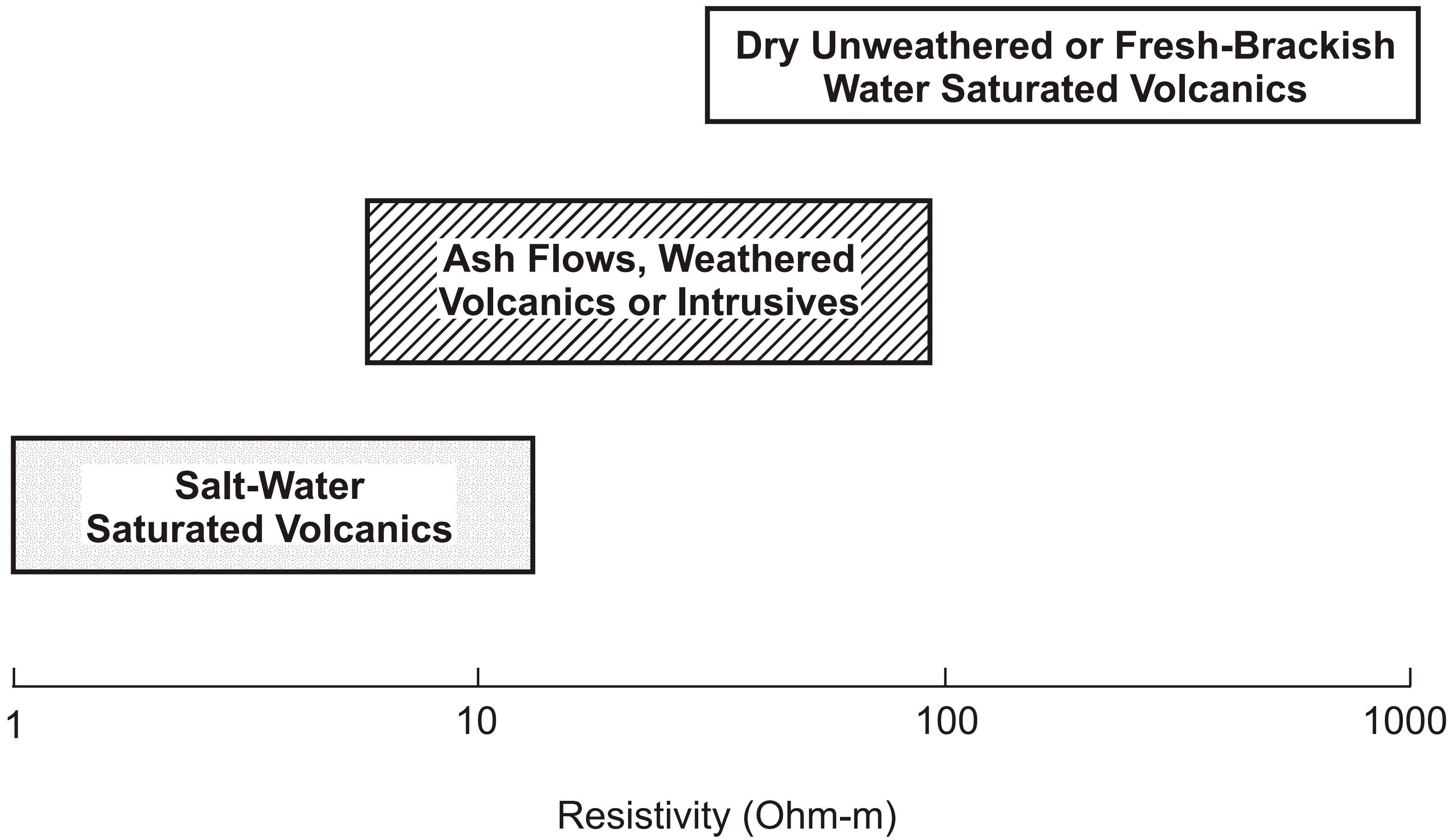
5067	March, 2007	HJV	RJB	No Scale	2-1



t = 1/40 (h)

BLACKHAWK A DIVISION OF ZAPATAENGINEERING	Tom Nance Water Resource Engineering Queen Liliuokalani Trust			**Illustration of the Ghyben-Herzberg Principle**			
301 Commercial Road, Suite B Golden, Colorado 80401 Phone: (303) 278-8700 Fax: (303) 278-0789 Web: www.blackhawkgeo.com	Project No: 5067	Date: March, 2007	Drawn By: HJV	Checked By: RJB	Scale: No Scale	Figure: 2-2	



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Characteristic Resistivity Ranges
Island of Hawaii

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3.0 DATA ACQUISITION AND LOGISTICS

Blackhawk mobilized a field crew consisting of a project geophysicist and geophysical technician to perform the geophysical surveys on the QLT property. The Blackhawk field personnel and TDEM equipment were mobilized from Golden, Colorado to Kailua-Kona, Hawaii. During the fieldwork TNWRE personnel provided project direction and oversight while QLT personnel provided project maps and site access (key to locked gate) to the property. A daily log of field activities during the TDEM surveys is presented in Table 3-1.

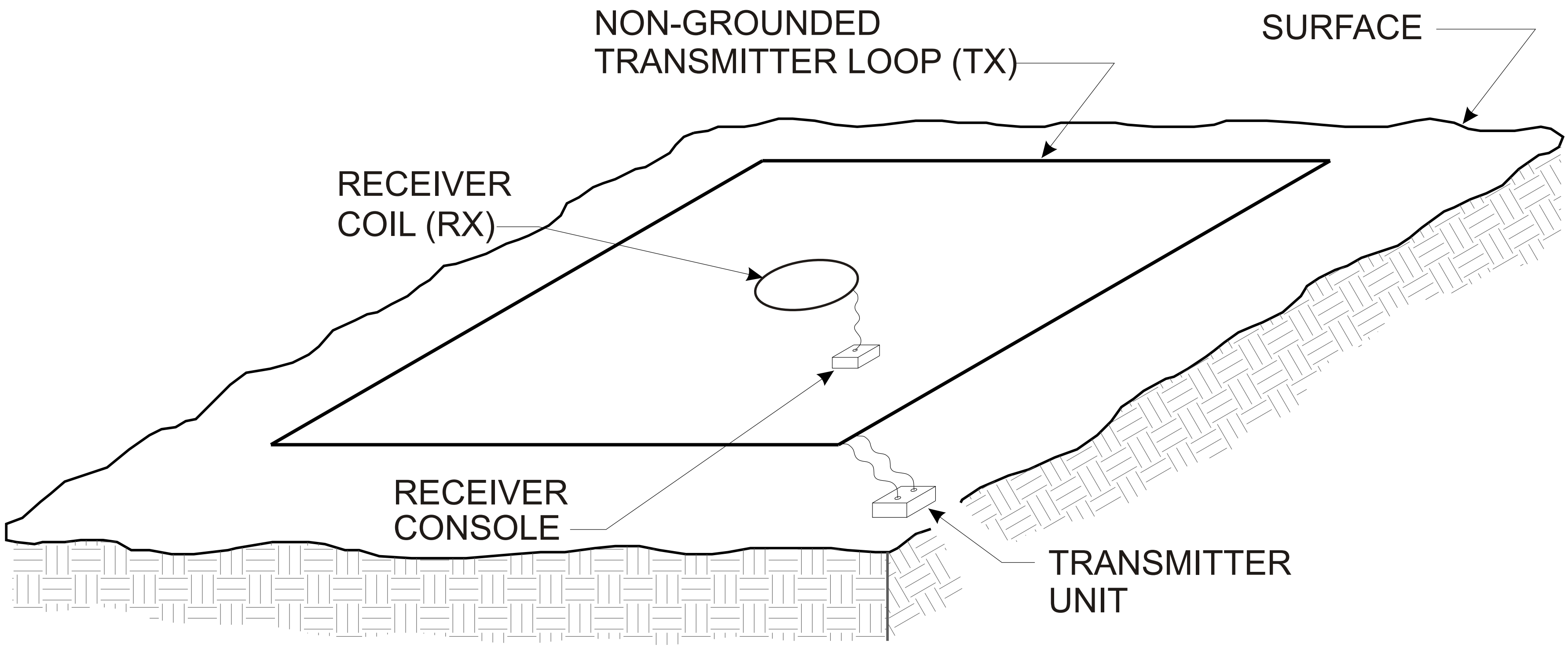
The geophysical equipment utilized for the TDEM surveys was the Geonics EM37 system. The EM37 system consists of both a portable motor-generator powered transmitter and a PROTEM digital receiver. The main purpose of the TDEM measurements is to derive both the vertical and lateral variations in the geoelectric section (resistivity) of the subsurface. To accomplish this, the TDEM measurements were acquired using a central-loop array at each sounding site. The square transmitter loops were constructed using 12-gauge insulated copper wire laid on the ground surface, as illustrated in Figure 3-1. The dimensions of the transmitter wire loops ranged from 1,000 ft by 1,000 ft to 1,250 ft by 1,250 ft. The motor-generator and transmitter were placed at a corner of the wire-loop and square-wave current pulses were driven through the wire using a current ranging from 12.5 to 15 amperes. The current pulses induce eddy current flow in the subsurface of the ground. A receiver coil (1-meter diameter) attached to the PROTEM receiver was positioned in the center of the wire-loop and used to record the decay of the secondary magnetic field due to the eddy currents induced in the subsurface. The effective exploration depth using a 1,000 ft by 1,000 ft transmitter wire-loop array has been determined to be approximately 2,500 ft. Greater exploration depths are reached with larger wire-loops and several factors that affect the depth of investigation include ground resistivity (ohm-m) and surrounding cultural interference (i.e. 60-cycle powerline, pipelines, etc).

The TDEM data acquired at each sounding consisted of measurements utilizing several receiver gain settings and two transmitter frequencies in order to ensure data quality and to obtain data over the longest possible time interval. The sounding data were recorded at base frequencies of 3 Hz and 30 Hz. For data quality control (QC) purposes, additional offset data sets were collected at designated locations (typically 100 ft) from the center of each sounding, for comparison to the central-loop data. The data from each sounding were stored in a solid-state memory logger in the PROTEM receiver and transferred at the end of each day to a PC for processing. The TDEM data collected with the PROTEM receiver were of excellent quality with none of the soundings being affected by nearby cultural interference (i.e. pipeline, powerline, etc.). A technical note describing the principles of TDEM with case histories is given in Appendix A.

The center and corners of each transmitter wire-loop were registered to the existing QLT Water Well located on the property. Other landmark features, such as QLT Water Well (4051-01) and paved access road were also used to locate the corners of the wire-loops on the map with a compass and hip-chain. In addition, a hand-held global positioning system (GPS) was utilized to map both the receiver and transmitter locations of each sounding. Due to dense tree canopy, the center location of Sounding QL-8 was not collected with the GPS. The GPS information was used to position each loop center on the geo-referenced topographic map and the elevation was subsequently taken from that position. A total of three soundings were measured on the QLT property during the four days of fieldwork. The GPS coordinates and elevations of the TDEM soundings, water well and water tank are given in Table 3-2 in Appendix B.

Table 3-1
Daily Log of Field Activities
QLT Property TDEM Survey

Date (2007)	Activity
January 16	Ship TDEM geophysical equipment from Golden, CO to Kona, HI.
January 22	Mobilize Blackhawk field personnel from Golden, CO to Kona, HI.
January 23-26	Unpack TDEM geophysical equipment at Kona Beach Hotel. Test motor-generator and organize equipment into 4WD vehicle. Work on other TDEM projects in Hawaii.
January 27	Receive gate key from QLT. Discuss project with TNWRE and QLT representatives, begin geophysical survey. Lay out and collect TDEM data on Sounding QL-7 (north of road). Download data to PC and perform preliminary data analysis in hotel. Discuss results with TNWRE.
January 28	Lay out and collect data on Sounding QL-8 (south of QLT Water Tank). Download data to PC and perform preliminary data analysis. Discuss results with TNWRE. Decision made by TNWRE to collect data on Sounding QL-9.
January 29	Brush survey line and carry in TDEM equipment (generator, etc.) to SE corner of Sounding QL-9 (500 ft north of road). Lay out east and north wires of transmitter loop. No data taken.
January 30	Continue lay-out of south and west wires of transmitter loop and collect data on Sounding WL-9. Carry out TDEM equipment and transmitter wires. Download data and perform data analysis in hotel. Discuss results with TNWRE. Finish QLT project.
January 31-February 12	Data on other projects in Hawaii. Deliver TDEM equipment to FedEx at Kona Airport. Demobilize Blackhawk personnel from Kona, HI to Golden, CO.



BLACKHAWK A DIVISION OF ZAPATAENGINEERING	Tom Nance Water Resource Engineering Queen Liliuokalani Trust	Schematic layout of TDEM system with locations of TX and RX for Central Loop Array measurements

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5067	March, 2007	HJV	RJB	No Scale	3-1

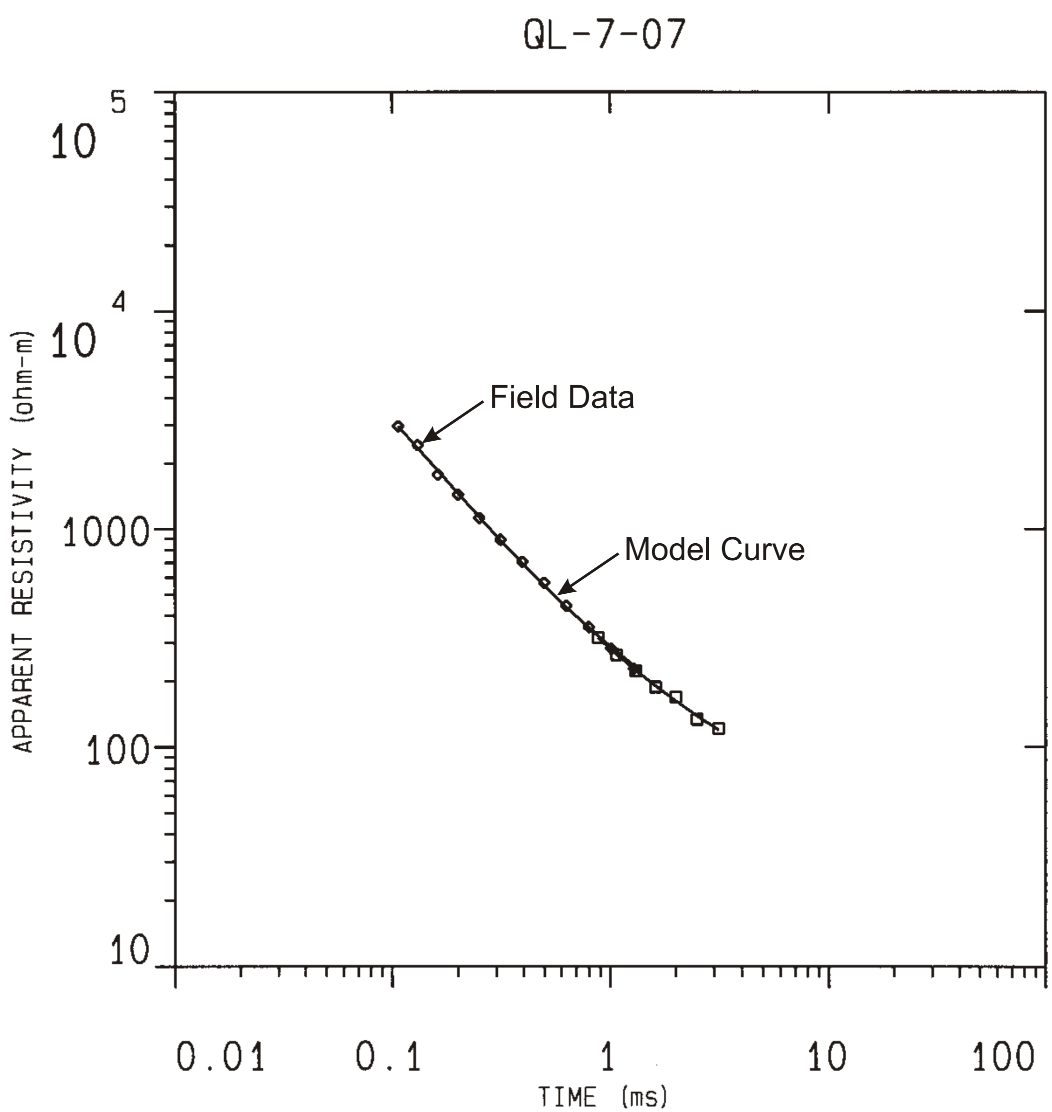
4.0 DATA PROCESSING

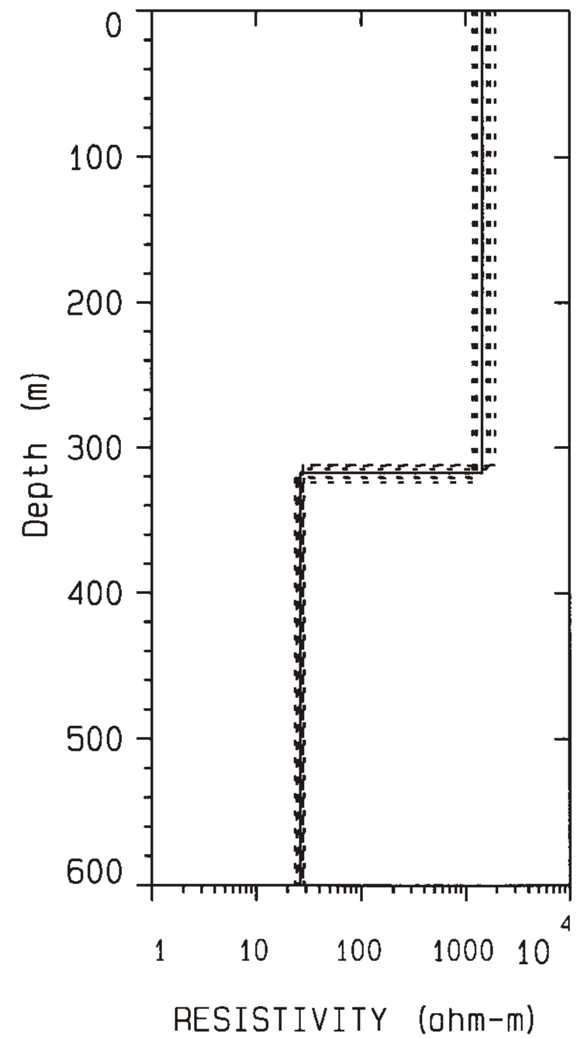
The field data collected for each TDEM sounding was transferred from the Geonics PROTEM digital receiver to a PC for editing and processing. Processing of the TDEM data starts with averaging of the electromotive forces recorded at positive and negative receiver polarities. Next, the measurements collected at the two base frequencies (3 and 30 Hz) and different amplifier gains are combined to give one voltage decay curve (transient). The electromotive forces in the various time gates of the decay curves were subsequently entered into the TEMIXXL (Interpex Ltd) inversion program to obtain a one-dimensional (1-D) geoelectric section that best matches the observed decay curve.

The TEMIXXL inversion program requires an initial model of the geoelectric section measured. The initial model includes the number of layers and the resistivities and thickness for each of the layers. This model is usually derived from general knowledge of the geologic section or from data obtained from drill holes or electric logs. The inversion program is then allowed to adjust the layer thickness and the resistivities, so that the model curve converges to best fit the field data. The inversion program does not change the total number of layers within the model curve, but allows all other parameters to change freely or they can optionally be fixed constant. To determine the influence of the number of layers on the solution, separate inversions with a different number of layers are run. Subsequently, the model with the least number of layers that best fits the field data is used.

An example of the output of the inversion program is shown on Figure 4-1 for Sounding QL-7-07. This figure shows the measured data points (in terms of apparent resistivity) superimposed on a solid line on the left panel. The solid line represents the computed forward model for the geoelectric section on the right panel. This geoelectric section is the best match obtained by the inversion program. Figure 4-2 shows the tabulated inversion parameters consisting of measured data, computed data for best match solutions and an example of the table of inversion statistics. A two-layer inversion model is shown for Sounding QL-7-07. The model displays a thick (1,041 ft) resistive upper layer (1,447 ohm-m) overlying a second intermediate resistive (26 ohm-m) layer. The depth to the top of the second layer is located at 628 ft above sea level in the section.

The interpreted geoelectric section derived from each TDEM sounding is not unique. The magnitude of each individual layer resistivity and thickness can normally be varied within a limited range with no significant change to the fit of the geoelectric model of the data. This variation is termed equivalence. An equivalence analysis was performed for each TDEM sounding. Figures 4-1 and 4-2 also show the equivalence analysis for Sounding QL-7-07. This sounding is typical of the TDEM data and shows a +/-5% equivalence in depth determinations and +/-10% in individual layer resistivities. The inversion results for each sounding of this project and previous 1991 data are given in Appendix B.





BLACKHAWK A DIVISION OF ZAPATAENGINEERING	Tom Nance Water Resource Engineering Queen Liliuokalani Trust			Sounding QL-7 Example Inversion Output Apparent Resistivity Curve *Queen Liliuokalani Trust Property* *Keahuolu Tract, Hawaii*		
301 Commercial Road, Suite B Golden, Colorado 80401 Phone: (303) 278-8700 Fax: (303) 278-0789 Web: www.blackhawkgeo.com	Project No: 5067	Date: March, 2007	Drawn By: HJV	Checked By: RJB	Scale: No Scale	Figure: 4-1

DATA SET: QL-7-07

CLIENT: TNWRE
LOCATION: Keahuolu, QLT Well and Tank
COUNTY: Hawaii
PROJECT: Queen Liliuokalani Trust
LOOP SIZE: 305.000 m by 305.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: E: 1.0000 N: 2.0000

DATE: 01-27-07
SOUNDING: 7
ELEVATION: 509.00 m
EQUIPMENT: Geonics PROTEM
AZIMUTH:
TIME CONSTANT: NONE
SLOPE: 1.00

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 3.439 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(ft)	CONDUCTANCE (Siemens)
			509.0	1670.0	
1	1446.8	317.5	191.4	627.9	0.219
2	26.20				

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	1177.741	1446.812	1924.141
	2	23.622	26.210	28.783
THICK	1	311.932	317.514	323.927
DEPTH	1	311.932	317.514	323.927

Equivalence Analysis

CURRENT: 15.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 4 RAMP TIME: 160.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.881	171.3	172.1	-0.495
2	1.06	138.3	136.9	1.02
3	1.31	107.0	105.9	1.06
4	1.61	81.66	80.46	1.46
5	2.00	55.99	59.84	-6.87
6	2.50	45.79	43.34	5.35
7	3.14	29.90	30.69	-2.63

CURRENT: 15.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 4 RAMP TIME: 160.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
8	0.106	1164.7	1165.6	-0.0747
9	0.131	942.0	985.5	-4.62
10	0.161	893.3	834.7	6.55
11	0.200	717.8	704.8	1.81
12	0.250	596.0	586.7	1.56
13	0.314	477.4	482.3	-1.04
14	0.395	381.0	390.4	-2.47
15	0.499	296.7	310.6	-4.68
16	0.631	237.5	243.3	-2.43
17	0.799	184.6	186.6	-1.05
18	1.01	143.4	140.5	2.05
19	1.28	108.1	103.4	4.37

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	T 1
P 1	0.46		
P 2	-0.13	0.88	
T 1	0.03	0.01	1.00

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Sounding QL-7
Example of Tabulated Data
From Inversion
Queen Liliuokalani Trust Property
Keahuolu Tract, Hawaii

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5057	March, 2007	HJV	RJB	No Scale	4-2

5.0 INTERPRETATION AND RESULTS

5.1 TDEM SOUNDING DATA

From each TDEM sounding, the geoelectric section of the subsurface is derived. The results of the one-dimensional (1-D) inversion of the individual TDEM soundings can be linked together (layers with similar resistivities) to create a 2-D geoelectric cross-section along a survey line. For this project, a total of three additional TDEM soundings were collected between previous data (1991) collected on the QLT property. Two geoelectric cross-sections were constructed from the combined TDEM survey data sets (1991 and 2007) and are shown on Figure 1-2. The correlations established between geoelectric layers and lithologic units (reference Figure 2-3) were used to interpret the geoelectric cross-sections.

5.2 GEOELECTRIC CROSS-SECTION – LINE 1 (A-A')

Figure 5-1 shows the layered geoelectric cross-section interpreted from the TDEM data taken along Line 1. This cross-section includes data from the present survey (Soundings QL-7 and QL-9) along with Soundings Q1 and Q6 taken in 1991. The TDEM soundings were positioned northwest of the QLT Well and at similar elevation as the QLT Water Tank and are situated in a west to east direction along the line. Sounding QL-7 was centered about 900 ft north of the paved road to the well (reference Figure 1-1). Sounding QL-9 was added to the survey after the data were collected on Soundings QL-7 and QL-8.

Two-layer cross-sections are interpreted beneath the four soundings along Line 1. The upper layer in the cross-section exhibits high resistivities that are >1,000 ohm-m and is interpreted as dry and clay poor volcanic formations above sea level. The second layer in the section (below Soundings Q1, QL-7 and QL-9) displays intermediate to high resistivities (26 to 102 ohm-m) and is interpreted to be influenced by geologic structures (e.g. intrusive, dikes, etc.) at depth in these soundings. The top of the second layer is interpreted to occur at an elevation of 395 ft above sea level beneath Sounding QL-9 and 628 ft above sea level at Sounding QL-7. The second layer in the section (beneath Soundings Q1, QL-7 and QL-9) exhibits interpreted resistivities which generally correspond to either significant amounts of fine-grained material (clays) or saturation with brackish groundwater. Both of these scenarios are unlikely in this area, and this strongly indicates that the soundings are distorted by two-dimensional (2-D) geologic structures. The TDEM soundings are interpreted assuming a one-dimensional (1-D) horizontally layered earth. When significant lateral changes in geology occur, the interpretation of the sounding may be distorted resulting in unrealistic models. Therefore, the three western TDEM soundings along this line are interpreted to be located within areas that are controlled by steeply dipping geologic structures that have distorted the true formation resistivities.

Sounding Q6 exhibited a high resistivity value (429 ohm-m) throughout the effective exploration depth of the measurement (approximately 1,000 ft below sea level). This sounding was interpreted to be located above the geologic/hydrologic structures (e.g. dikes) that were inferred to be located beneath the soundings to the west. The QLT Well was drilled at elevation 1,765 ft and has a head of 188 ft (per com Tom Nance), which produces water from a high-level groundwater resource. Thus, with the existing TDEM data density, the geologic/hydrologic boundary is interpreted to be located between Sounding QL-7 and the QLT Well. The exact position and width of the geologic structure is uncertain due to the TDEM data density in this area.

5.3 GEOELECTRIC CROSS-SECTION – LINE 2 (B-B')

The layered geoelectric cross-section interpreted from the data collected along Line 2 is shown in Figure 5-2. Sounding QL-8 was located 700 ft south of the QLT Water Tank at an elevation of 1,730 ft. This cross section includes data from the present survey Sounding QL-8 and Sounding Q6 taken in 1991.

A two-layer geoelectric cross-section is interpreted for the soundings along Line 2. The upper layer in the cross-section shows high resistivities that are >1000 ohm-m and is interpreted as dry clay poor volcanic formations above sea level. The second layer, beneath Sounding QL-8, exhibits an intermediate resistivity of 36 ohm-m and is interpreted to be influenced by geologic structures at depth. The top of the second layer is interpreted to occur at elevation of 786 ft above sea level. The second layer (beneath Sounding QL-8) is expected to be influenced by 2-D geologic structures (e.g. intrusive, dikes).

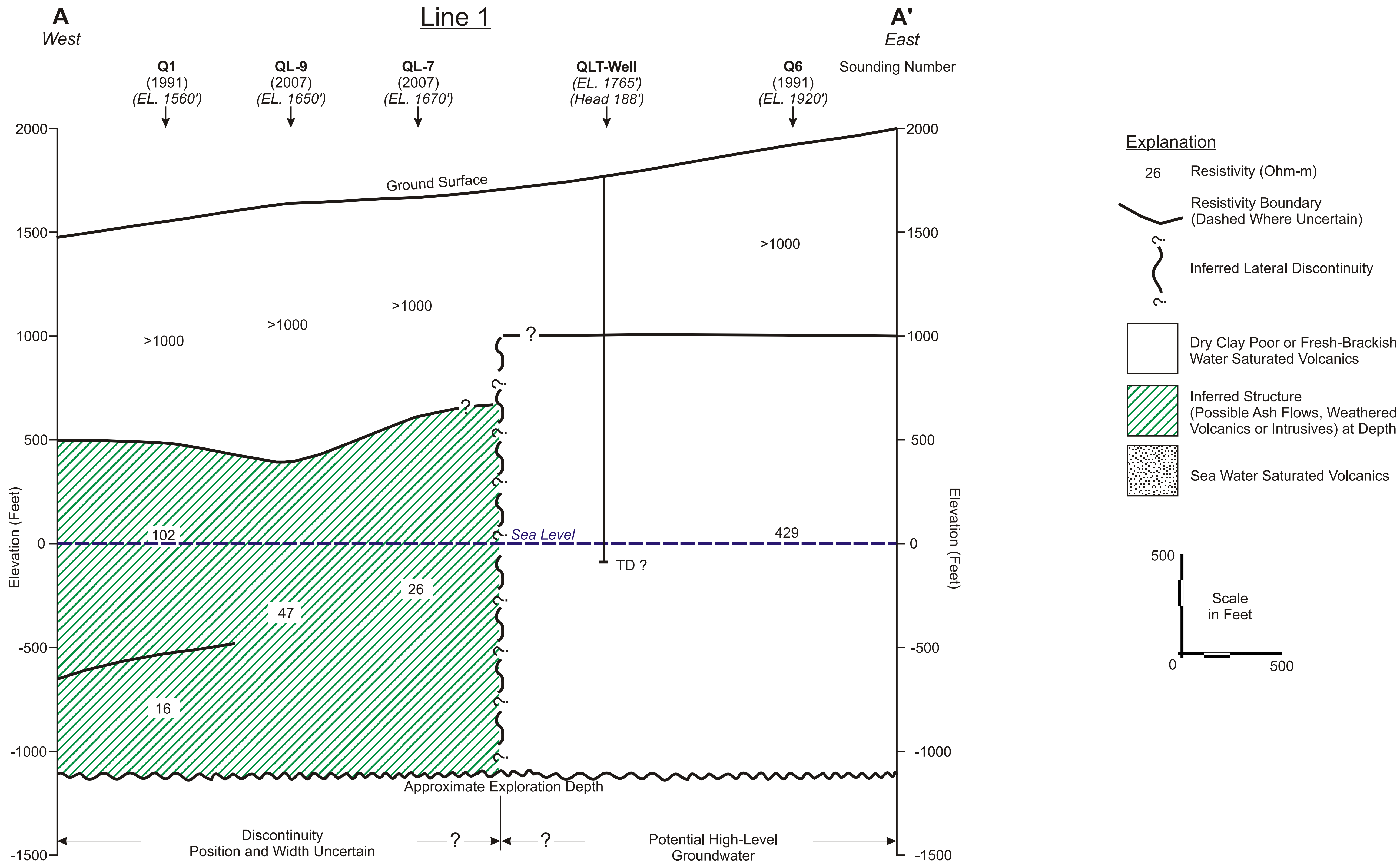
Again, Sounding Q6 exhibited a high resistivity value of 429 ohm-m throughout the effective exploration depth of the measurement. This sounding was interpreted to be located above the geologic/hydrologic structures (e.g. dikes) that were observed beneath Sounding QL-8. Considering the distance (1,500 ft) between TDEM sounding centers along this line, the placement of the geologic/hydrologic boundary is interpreted to be located between Soundings QL-8 and Q6. With this information, the exact position and width of the geologic structure is uncertain due to the TDEM data density in this area.

5.4 HYDROGEOLOGIC INTERPRETATIONS

The TDEM data from the survey is further summarized on the interpretation map shown in Figure 5-3. On this map the data taken during the recent 2007 survey are combined with the 1991 survey. The soundings are separated into two main groups and are color coded:

1. Soundings Q1, QL-7, QL-8 and QL-9 (green) are interpreted to be influenced by lateral discontinuities (e.g. intrusive, dikes) and geologic/hydrologic groundwater damming structures are inferred. Intermediate resistivity values (16 to 47 ohm-m) occur above and below sea level and therefore groundwater levels, water quality and production are expected to be variable in these areas.
2. Sounding Q6 (yellow), where a high resistivity value (429 ohm-m) was interpreted to the effective exploration depth of the sounding (about 1,000 ft below sea level). The potential for high-level groundwater exists in the area of this sounding.

From the summary map, the placement of the upper boundary of the inferred geologic/hydrologic discontinuity appears to be located between Sounding QL-7 and the QLT Well on the west; and between Soundings QL-8 and Q6 to the southwest.



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Geoelectric Cross-Section
from 1-D TDEM Inversions
Line 1 - Transect A-A'
Queen Liliuokalani Trust Property
Keahuolu Tract, Hawaii

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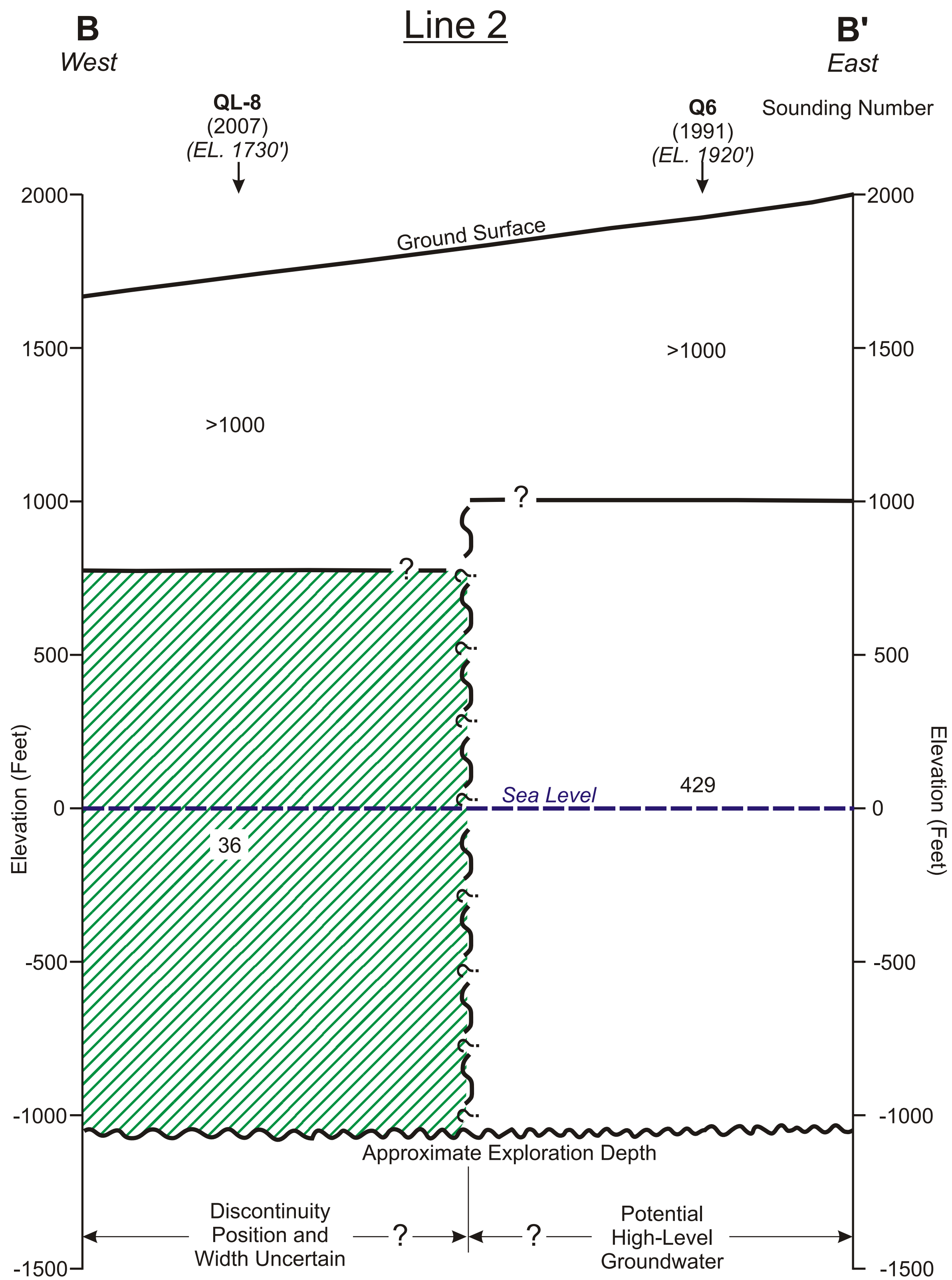

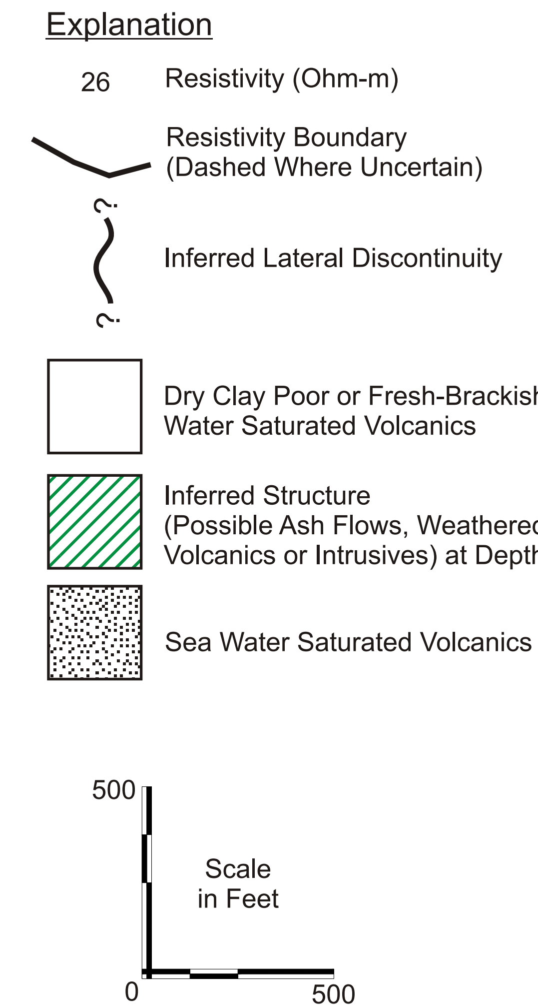

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Geoelectric Cross-Section
from 1-D TDEM Inversions
Line 2 - Transect B-B'
Queen Liliuokalani Trust Property
Keahuolu Tract, Hawaii

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5067	March, 2007	HJV	RJB	1”=500”	5-2

6.0 CONCLUSIONS AND RECOMMENDATIONS

The main objective of the TDEM surveys on the QLT property on Hawaii was to explore for additional high-level groundwater resources in the vicinity of the QLT Water Tank. The optimum locations for high-level groundwater are expected to occur within or above dike-confining areas detected with TDEM soundings at relatively low surface elevations.

The results from the combined 2007 and 1991 TDEM data sets are shown on the summary map in Figure 5-3. The TDEM data indicate:

- That in areas beneath Soundings Q1, QL-7, QL-8 and QL-9, the data are interpreted to be influenced by lateral discontinuities (e.g. intrusives, dikes) and groundwater-damming structures are inferred. The groundwater regime is expected to be structurally complicated in these areas and groundwater yield and quality is expected to be variable.
- Beneath Sounding Q6, the potential for high-level groundwater exists. With the present data, groundwater damming structures are interpreted downhill of Sounding Q6 and on two sides, west and southwest. The QLT Well is located downhill of Sounding Q6 at ground elevation 1,765 ft (188 ft head) and produces from a high-level groundwater resource.

The general conclusions from the summary map are that the upper boundary of the inferred geologic/hydrologic discontinuity appears to be located between Sounding QL-7 and the QLT Well on the west side. Between Soundings QL-8 and Q6 and towards the south, the inferred boundary appears to increase elevation and trends uphill. From the present TDEM survey and well data it appears that the area north of the QLT Well has the greatest potential for high-level groundwater production.

Additional TDEM soundings located east (uphill) of Sounding QL-7 will help define the extent of the boundary of potential high-level groundwater towards the north of the QLT Well in this area of the property.

7.0 CERTIFICATION AND DISCLAIMER

All geophysical data analysis, interpretations, conclusions, and recommendations in this document have been prepared under the supervision of and reviewed by ZAPATA ENGINEERING P.A. Blackhawk Division, Senior Geophysicists and Engineers.

This geophysical investigation was conducted using sound scientific principles and state-of-the-art technology. A high degree of professionalism was maintained during all aspects of the project from the field investigation and data acquisition, through data processing, interpretation, and reporting. All original field data files, field notes and observations, and other pertinent information are maintained in the project files and are available for the client to review.

A geophysicist's certification of interpreted geophysical conditions comprises a declaration of his/her professional judgment. It does not constitute a warranty or guarantee, expressed or implied, nor does it relieve any other party of its responsibility to abide by contract documents, applicable codes, standards, regulations, or ordinances.

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